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INVESTIGATION OF THE ESCAPE OF CHARGED PARTICLES FROM A PLASMA IN A MAGNETIC FIELD

L. L. Pasichnyk and O. V. Kozak

Recently a number of works [1-6] were published on the anomalous diffusion of charges in a plasma in a magnetic field. A comparison of experimental results of various authors points to the complexity of the phenomena involved under such conditions and to the possible existence of different mechanisms of increased emergence of particles from a plasma.

The present work deals with the emergence of charges from a hot-cathode plasma under low pressure, in a magnetic field. At the same time, the spectrum of high frequency oscillations (0.02-30 Mc/s), generated by the discharge, was investigated.

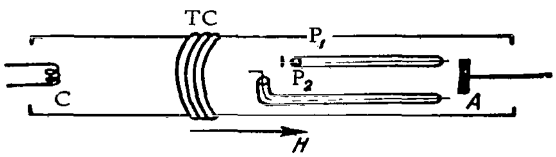

Fig. 1. Experimental tube.

Figure 1 shows schematically the experimental lamp. The plasma was created by means of a hot tungsten cathode C in a quartz tube (77 mm in diameter and 750 mm in length). The tube was continuously evacuated; the residual-gas pressure in the system did not exceed $1 \cdot 10^{-6}$ mm Hg; the normal working-pressure was (1-10) x 10^{-3} mm Hg. The discharge column was in a homogeneous magnetic field of up to 2000 oersted. The central part of the tube contained the mobile probe P 1(0.3 mm diameter, 8 mm long), which could be placed at any point of the discharge cross-section, and the fixed flat probe P_2. The electromagnetic oscillations generated by the discharge were studied by means of testing coil TC, wound around the tube. The signal from the coil arrived at the input of the noise-spectrum analyzer АСШ-4, (ASSh-4), by means of which visual observations of the oscillations in the 20 kc/s-30 Mc/s range were made.

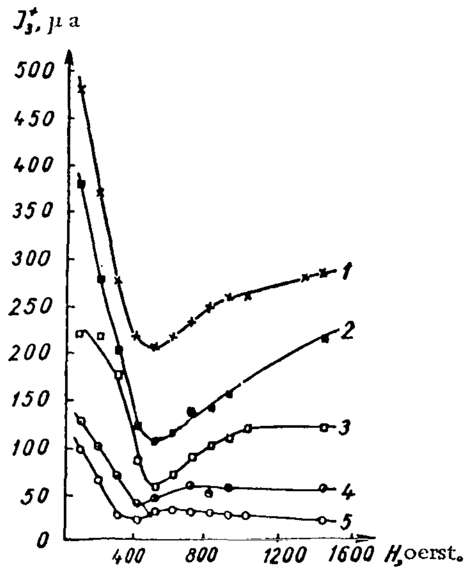

Fig. 2. Dependence of probe current on magnetic field. Discharge in hydrogen, $U_d = 110$ volt, $p = 2.5 \cdot 10^{-3}$ mm Hg. Curve 1 — $J_d = 1200$ ma; 2 — $J_d = 850$ ma; 3 — $J_d = 200$ ma; 4 — $J_d = 50$ ma; 5 — $J_d = 25$ ma.

Figure 2 shows the dependence on the magnetic field, of the ion current of the cylindrical probe, placed at a distance of $l = 16$ mm. from the column axis. It is evident from the figure that the curves $J_3 = f(H)$ have a sharp minimum for certain values of the magnetic field H_{cr}. Critical magnetic fields H_{cr} were also observed in the case of discharges in helium and nitrogen. For discharges in heavier gases (argon, krypton), the dependence $J_3^+ = f(H)$ is a monotonically-decreasing curve (up to values of H=2000 oersted) for any parameters of the discharge. It is characteristic that the abnormally high emergence of charges from the plasma is observed only after keeping the discharge tube for a fairly long time under operating conditions, when impurity traces appear in the discharge spectrum. These spectra were obtained on the spectrograph ICП-51 (ISP-51). On passing to critical magnetic fields, the plasma column as a whole expanded.

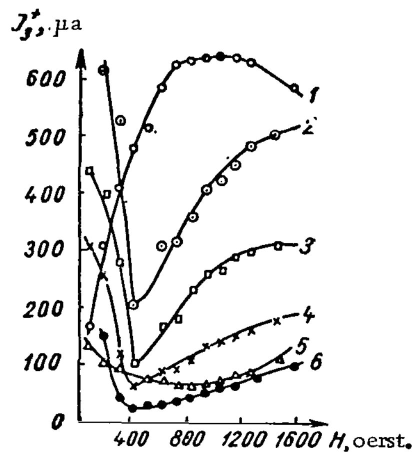

Fig. 3. Dependence of probe current on magnetic field. Discharge in hydrogen, J_d =450 ma., U_d =110 volt. Curve

1 — l = 0; 2 — l = 8 mm; 3 — l = 12 mm; 4 — l = 16 mm; 5 — l = 20 mm;

6 — l = 24 mm.

Figure 3 shows the dependence $J_3^+ = f(H)$ for various distances between probe and column axis. When the probe lies on the column axis, an increase in magnetic field leads initially to an increase in probe current as a result of column contraction; for $H > H_{cr}$, the charge concentration on the axis decreases as a result of column expansion (curve 1). An increase in the distance between probe and axis leads to changes in the curves $J_3^+ = f(H)$ (curves 2 - 6). It is remarkable that the ratio of electron - to ion current remains thereby practically unchanged (Fig. 4). For $H = H_{cr}$ (curve 2), the ion -, as well as the electron part of the probe characteristic, lie below the corresponding parts of the characteristic for both $H < H_{cr}$ (curve 1) and $H > H_{cr}$ (curve 3). This result is essentially different from the results of A. V. Zharinov [4], who obtained at the critical field values a sharp increase in the electron - to ion probe-current ratio.

The critical value of the magnetic field H_{cr} depends weakly on the discharge current (J_d), which determines the density of the plasma in the discharge (Fig. 2). When J_d changes from 25 to 1200 milliamp., H_{cr} increases

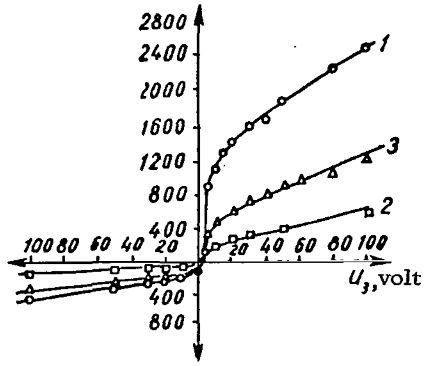

Fig. 4. Current-voltage characteristic of probe current. Discharge in hydrogen, J_d = 450 milliamp, U_d = 110 volt,

p = 3 · 10³ mm. Hg. Curve 1 — H = 200 oersted;
2 — H = 500e;3 — H = 1200e.

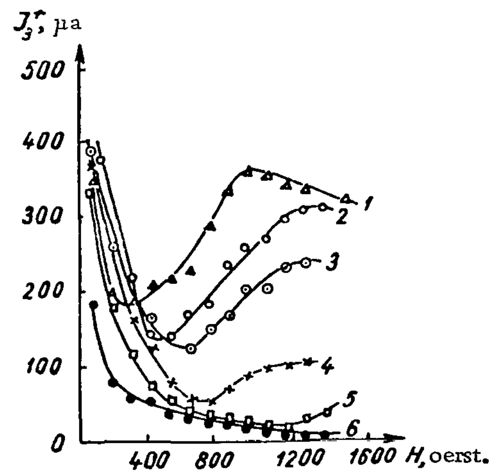

Fig. 5. Dependence of probe current on magnetic field. Discharge in hydrogen, J_d = 450 milliamp., U_d = 110 volt, l = 16 mm.

Curve 1 — p = $1.2 \cdot 10^{-3}$ mm. Hg; 2 — p = $2.4 \cdot 10^{-3}$ mm. Hg;
3 — p = $4.4 \cdot 10^{-3}$ mm. Hg; 4 — p = $5.7 \cdot 10^{-3}$ mm. Hg;

5 — p = $6.2 \cdot 10^{-3}$ mm. Hg; 6 — p = $1.6 \cdot 10^{-2}$ mm. Hg.

only from 400 to 550 oersted; H_{cr} also depends weakly on the discharge-tube voltage (U_d).

H_{cr} depends most strongly on the gas pressure (Fig. 5). H_{cr} increases with the pressure, and the effect of abnormal column-expansion itself becomes less pronounced. Similar results were obtained in the case of discharges in helium and nitrogen. Figure 6 shows the dependence of the critical magnetic field on the pressure for discharges in hydrogen (curve 1) and helium (curve 2).

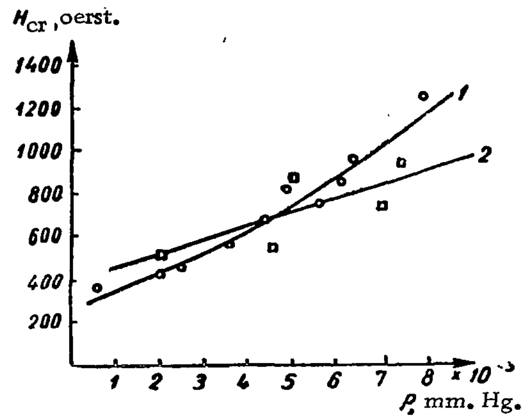

Fig. 6. Dependence of critical magnetic field on pressure. J_d = 450 milliamp., U_d = 110 volt. Curve 1 — discharge in hydrogen; 2 — discharge in helium.

A study of the noise spectrum by means of the ASSh-4 analyzer showed that the increased emergence of charges from the plasma is always accompanied by the generation of electromagnetic waves, for $H \sim H_{cr}$. Figure 7 shows a number of oscillograms of the oscillation spectrum, generated by a discharge in helium under various magnetic fields ($H_{cr} \approx 330$ oersted, the left-hand arrow corresponds to zero frequency and the right-hand arrow to 15 Mc/s). From Fig. 7 it is evident that the intensity of oscillations increases with H (for $H > H_{cr}$). The oscillations are distributed over a frequency range of 5 to 7 Mc/s, and have as a rule sharp boundaries on both sides. Similar results were also obtained in the case of hydrogen and nitrogen (Fig. 8). A change in the orientation of the testing coil with respect to the discharge axis does not practically affect the magnitude and nature of the oscillations.

By comparing the dependence on the magnetic field of the intensity of oscillations (Fig. 9, curves 1a, 2a, 3a) and of the probe current (curve 1, 2, 3), it is evident that the intensity of oscillations is closely connected to the expansion of the plasma column. In all three cases considered, the oscillations arise

Fig. 7. Oscillation-spectrum oscillograms. Discharge in helium, J_d = 450 milliamp., U_d = 110 volt, $p = 2.5 \cdot 10^{-3}$ mm. Hg. Curve 1 — H = 200 oersted; 2 — H = 300 oersted; 3 — H = 400 oersted; 4 — H = 500 oersted.

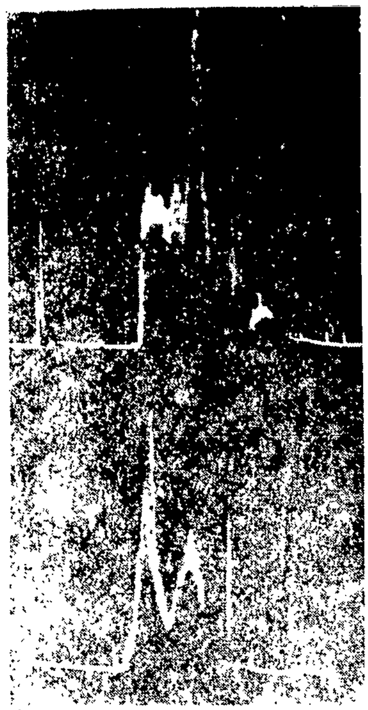

Fig. 8. Oscillation-spectrum oscillograms. 1 — discharge in nitrogen, J_d= 450 milliamp., U_d = 300 volt, H = 1200 oersted, $p = 1 \cdot 10^{-3}$ mm. Hg.; 2 — discharge in hydrogen, J_d = 450 milliamp, U_d = 110 volt, H = 1300 oersted; $p = 2 \cdot 10^{-3}$ mm. Hg.

when the curve $J_3 = f\ (H)$ passes through a minimum; an increase in probe current is accompanied by an increase (by a factor of 10^3 - 10^4) in the intensity of oscillations. The gas pressure has a considerable effect on the intensity of oscillations (Fig. 10). An increase in pressure leads to a steadfast

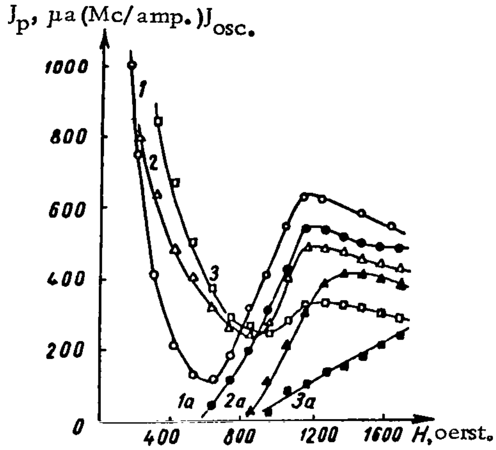

Fig. 9. Dependence of oscillation intensity and of probe current on the magnetic field. Discharge in hydrogen, Curve 1 — J_p, 1a — J_{osc}; discharge in helium, 2 — J_p, 2a — J_{osc}; discharge in nitrogen, 3 — J_p, 3a — J_{osc}.

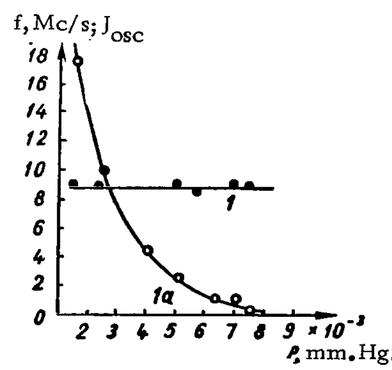

Fig. 10. Pressure dependence of frequency and intensity of oscillations. J_d = 450 milliamp., H = 1200 oersted, U_d = 110 volt. Discharge in helium, curve 1 — f_{osc}, 1a — J_{osc}.

decrease in the intensity of oscillations (Curve 1a). This result is in good agreement with the data on the pressure dependence of column expansion. Thereby the frequency spectrum of the oscillations changes little (curve 1). Changes in U_d and J_d have also little effect on the frequency spectrum of the oscillations. In our experiments, it was established that the cathode region of the discharge has a considerable influence on the generation of oscillations: in order that intense oscillations should appear, it is necessary that the condition $H > H_{cr}$ be fulfilled in the cathode region. A change in magnetic field in the anode region has no appreciable effect on the intensity of oscillations, which hardly changes along the discharge tube. Hence, if the magnetic field in the cathode region is less than its critical value, there are no oscillations in either cathode or anode region of the discharge, although the magnetic field in the anode region exceeds by far H_{cr}.

The above experimental data are proof of the direct connection between the expansion of a plasma column and the high-frequency oscillations which arise in the plasma.

The frequency spectrum of the oscillations which arise in the plasma shows that these oscillations cannot be interpreted on the basis of the theory of V. B. Kadomtsev and A. V. Nedospasov [7]. The weak dependence of the frequency of oscillations on the magnetic field and on the discharge current shows that these oscillations cannot be related to ion-cyclotron or Langmuir oscillations.

We are of the opinion that the oscillations which appear can be related to an upset in the stability of the layer adjacent to the cathode of the discharge. According to D. Bohm [8], the stability condition of this layer is:

$$\frac{j_i}{j_e} \geqslant \alpha \sqrt{\frac{m_e}{m_i}}. \quad (1)$$

where j_e is the density of the electron current from the cathode, j_i is the density of the ion current on the boundary between layer and plasma near the cathode; m_e and m_i are the mass of the electron and ion respectively, and α is a numerical factor of the order of unity. This criterion was obtained by D. Bohm in studying the question of the minimum pressure necessary for maintaining a stable arc discharge in a magnetic field.

The existence of H_{cr} can be explained by taking into account the fact that the ratio j_i/j_e decreases with increasing magnetic field. The electron current from the cathode is determined by the cathode temperature and by the voltage on the discharge tube. A longitudinal magnetic field does not appreciably affect the current from the cathode; the quantity j_e can be taken as constant, since already for fields H = 100 oersted, the condition $r_{Lar} \ll d_{cat}$ always holds (r_{Lar} is the Larmor electron-radius, and d_{cat} the cathode diameter). The ion-current density is

$$j_i = \beta p \lambda j_e, \tag{2}$$

where p is the pressure, λ the number of ionizations per electron per 1 cm. of path, and β a constant. It is well-known [8] that λ decreases with increasing magnetic field. Therefore, condition (1) can be upset for certain magnetic field values. Numerical estimates, based on experimental data, show that for $H \approx H_{cr}$ the ratio j_i/j_e is close to $\sqrt{\frac{m_e}{m_i}}$. In the case of a discharge in hydrogen for J_d = 450 milliamp., U_d = 110 volt, $p = 2.5 \cdot 10^{-3}$ mm. Hg, the ion-current density in the plasma near the discharge axis is close to $4.2 \cdot 10^{-2}$ amp./cm^2; the density of the electron-current from the cathode $j_e \approx 2.2$ amp./cm^2; their ratio is approximately $1.9 \cdot 10^{-2}$. Hence, the value of $\sqrt{\frac{m_e}{m_i}}$ for a discharge in hydrogen is $2.3 \cdot 10^{-2}$.

If condition (1) is upset, the primary-electron beam is modulated; a modulated electron beam, which passes through a plasma, excites in it oscillations which cause an increased emergence of charged particles from the plasma. In order to find the spectrum of the arising oscillations, it is necessary to solve the self-consistent problem for the system beam-cathode-adjacent layer-plasma.

Such a scheme permits of explaining a number of experimental facts: the presence of a critical magnetic field; the role of the cathode-adjacent layer in the development of oscillations; the uniform distribution of the intensity of oscillations along the discharge column; the strong dependence of H_{cr} on the pressure and its weak dependence on the discharge current. Such an explanation is based exclusively on qualitative considerations and therefore cannot be regarded as sufficiently complete and unambiguous.

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